CONFERENCES AND SYMPOSIA

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Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (25 December 1996)

A Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held on 25 December 1996 at the P L Kapitza Institute for Physical Problems. The following reports were presented at this session:

(1) **Ozerov R P** (D I Mendeleev University of Chemistry and Technology, Moscow) "Neutronography: history and trends of further progress";

(2) **Aksenov V L** (Joint Institute for Nuclear Research, Dubna) "Current methods of structural neutronography";

(3) **Izyumov Yu A** (Institute of Metal Physics, Ekaterinburg) "Physical basis of magnetic neutronography";

(4) **Rumyantsev A Yu** (Russian Research Center 'Kurchatov Institute', Moscow) "Neutron studies in the RRC 'Kurchatov Institute''

(5) **Maleev S V** (St. Petersburg Nuclear Physics Institute, Gatchina) "Neutron scattering and investigations in solid state physics in the St. Petersburg Nuclear Physics Institute"

Summaries of the four reports are given below.

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Neutronography: history and trends of further progress

Ozerov R P

The neutron was discovered by J Chadwick in 1932. This discovery had a great impact on the development of mankind. In particular, the use of neutron scattering as a method of research considerably promoted progress in modern science and technology.

Only two years after Louis de Broglie had suggested his formula relating the corpuscular and wave hypotheses of particle motion (1924), its validity was confirmed by electron diffraction studies (1927). It was natural that the discovery of the neutron gave impetus to experiments designed to verify corpuscule-wave dualism taking advantage of this 'massive' particle. Three papers were simultaneously published in 1936 (that is, around three to four years after the discovery of the neutron). One of them (see Ref. [1]) was a theoretical study of neutron passage through polycrystals which showed a somewhat enhanced transmittance at a neutron wavelength exceeding the two largest interplane distances of the crystal specimen. Another work [2] provided experimental confirmation of this effect. The third paper by Mitchell and Powers [3] looks especially convincing since it confirms Bragg scattering in its modern sense.

Neutron diffraction experiments were impracticable at that time because the intensity of Ra – Ba sources was very low. In the meantime, the theory of neutron interaction with nuclei and atoms was being extensively developed. Bloch [4, 5] investigated magnetic neutron scattering using magnetically ordered crystals (largely ferromagnetics) while Halpern and Johnson [6] showed that magnetic scattering is even more prominent in paramagnetic crystals. Breit and Wigner [7] developed the theory of interaction between neutrons and nuclei (scattering and absorption) on the assumption that the nucleus has only one excited level. This theory was later applied to the classification of experimentally measured neutron cross-sections.

Experiments of a new type (closer to their current versions) were performed on nuclear reactors which were then called 'boilers'. The first reactor designed by a group lead by E Fermi was commissioned in Chicago at the end of 1942. The first reactor on the Euro-Asiatic continent was commissioned 50 years ago (1946) in Moscow. The work was headed by I V Kurchatov. These reactors were not suitable for neutron beam experiments. A special reactor for this purpose was constructed at Oak Ridge, USA, at the end of 1943. In the years that followed, pioneer works on neutron scattering were carried out which laid the foundation of neutronography as a method used by solid state physics.

The appearance of these reactors provided the basis for designing neutronographic facilities for structural characterization of crystalline objects by their neutron-scattering capacity. These instruments had units for neutron monochromatization by means of mechanical interruption of continuous polychromatic neutron beams (the so-called 'choppers' first proposed by E Fermi) or by their reflection from monocrystals. The first one-axis crystal spectrometer designed by W Zinn [8] was largely used to measure cross-sections of nuclear reactions involving neutrons. Moreover, the so-called 'swing curves' were obtained for the first time with the help of this instrument and pioneering neutronographic studies were carried out which eventually gave rise to an effective new method for structural analysis and the investigation of solids. The most important in this respect was a paper by Fermi and Marshall [9] in which the authors explored the possibility of employing neutron diffraction in physics and chemistry of crystals and measured scattering amplitudes (lengths) for more than 20 nuclei including those with negative values of this parameter.

We mostly owe further achievements in neutronography as a method of research to two physicists, Ernest Wollan and Clifford Shull. By that time, Wollan (1902 – 1984) was a highly reputed researcher who had long worked with X-rays and could apply his experience to neutron studies. Shull (born

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in 1915) graduated from the Carnegie Technological Institute in 1937 and received his Ph.D. degree in nuclear physics in 1941 from the University of New York. In 1946, he joined the Oak Ridge National Laboratory and took an active part in designing neutronographic facilities and conducting experiments. He was later involved in joint projects at different laboratories (1946 – 1969) and had many pupils. Even an incomplete list of Shull's works gives the idea of his role in the establishment and progress of neutronography. Specifically, he proposed methods for measuring cross-sections of coherent and incoherent neutron scattering including that induced by isotopic and spin incoherence, monochromators (halogenides and metallic monocrystals), radioprotective systems for monochromators, photography of neutron diffraction patterns (revived now by G Smith of the Neutronics Co), two and three axis neutron diffractometers (e.g. making use of polarized neutrons). Shull's pioneering works also include the location of protium and deuterium atoms in sodium hydride and the location of protium in ice, the investigation of ordering in alloys composed of metals with close atomic numbers, the determination of magnetic moments of atoms in alloys, the measuring of form-factors of magnetic scattering by many elements from different groups of Mendeleev's Periodic Table, etc. The first reports appeared in 1948 [10]. It is worthwhile to mention specially such great events as the discovery of antiferromagnetic ordering and the introduction of the term 'magnetic structure of crystals' into the language of science, the investigations into the distribution of magnetization in iron, the corroboration of electron 'pairing' (Cooper pairs) in superconductors, the studies on dynamic effects in neutron scattering by ideal crystals, the demonstration of the previously predicted 'Schwinger' neutron scattering, etc. Diagrams, pictures, and results from Shull's original publications are lavishly cited in books and reviews.

In parallel with these studies, neutron spectroscopy was being developed. The works of B N Brockhouse (born in 1918) are of special value for this field. Brockhouse worked in the Chalk-River Laboratory, Canada, which he joined after having graduated from the Universities of British Columbia and Toronto. A group headed by Brockhouse commissioned the first three-axis neutron spectrometer and measured elastic incoherent scattering (by vanadium); these studies gave rise to neutron spectroscopy.

G E Bacon started his works at Harwell (UK) in 1946. The crystal spectrometer of his design was made by "John Carran" Co and installed at the VERO research reactor. In 1948, he published (jointly with R Loud) results of a study on the reflecting power of monocrystals which related neutron scattering observations to what had been known about X-ray interactions with crystals. A major contribution to neutronography was made by Bacon's pioneers studies on the role of hydrogen atoms and hydrogen bonds in the physical properties of crystals. His basic study on the structure of KH_2PO_4 and its temperature dependence had great influence on the development of the science of segnetoelectricity. His works on the magnetism of metals and alloys are equally well-known. Professor Bacon wrote the book entitled "Diffraction of Neutrons" first published in the UK in 1954 (3rd edition in 1975) [11]. The first edition of this book was translated into Russian and published here in 1957 [12].

The first Soviet reactors were not suitable for neutron beam experiments, being constructed for military purposes in the atmosphere of the armaments race. At that time, much attention was given to the analysis of literature. We, as students at the Moscow Engineering and Physics Institute (MEPI), were very enthusiastic about what seemed to be a challenging problem (which it really was) and organized a students' scientific society to further collection of information and discussion of the subject. I was glad to serve as the deputy of N G Basov who even then showed promise of becoming a prominent scientist. Professor G S Zdanov, my teacher, who headed the Department of Roentgenography, MEPI, and B M Levitskiĭ, Assistant Professor at the same department, were the first to draw my attention to the recent publications of the above authors who had used neutron diffraction to study crystal structure. I made a review of the small materials available at that time which was published in *Uspekhi Fizicheskikh Nauk* on the initiative of E V Shpol'sky, Editor-in-Chief. Afterwards, fresh results of research in this field were also published and analysed in this journal [13].

In 1957, I was a research fellow at the L Ya Karpov Physico - Chemical Institute (PCI) attached to the I V Kurchatov Institute of Atomic Energy (KI) for work on the IRT reactor.

Like many others in the country, we had to begin from the beginning because there was no home manufacture of neutron counters, crystalline monochromators, cryostats, heaters, and neutron spectrometers; nor did industry have any incentive to produce them. We used commercially-available universal X-ray diffractometers for structural studies (URS). A massive protective screen that wholly covered the diffractometer was made to reduce effect of background neutrons present in the reactor building. All this work was done by my group consisting of I D Datt and the now deceased N V Rannev, S V Kiselev, V P Smirnov; A A Loshmanov and V I Goman'kov joined us later.

Neutronographic studies were being conducted at that time by several institutes and research groups having their own reactors or in cooperation with those interested in the problem and the 'owners' of neutrons. I I Yamzin and his postgraduate student Yu Z Nozik of the Institute of Crystallography, USSR Academy of Sciences, worked on the reactor at the Institute for Experimental and Theoretical Physics (ITEP) together with Yu G Abov of this institute. These people were brought together by common interest in the physical properties of ferrites. Yu Z Nozik focused on oxides having a spinell structure while I I Yamzin with a group of postgraduate students studied (a bit later) the magnetic structure of long-periodic hexagonal ferrites.

B G Lyashchenko, D F Litvin and their colleagues of the Institute of Ferrous Metallurgy were attached to ITEP where they investigated the inhomogeneity of alloys by neutron spectroscopy.

One of the most important works of those days was made by V N Bykov and other members of the group headed by N V Ageev on the reactor of the first nuclear power station at Obninsk (today, the Physics and Energy Institute). They discovered satellites of the main magnetic reflections of metallic chromium which were simultaneously reported to exist by J Hastings and L Corliss of the Brookhaven National Laboratory, USA. These works gave impetus to a number of related studies designed to account for the above findings based on the helicoid magnetic structure. This 'detective story' with the race, disputes about priority, more and more complicated models, achievements, and disappointments is vividly described in the book of G E Bacon [11].

All these people soon became friends with whom I was happy to work in close contact.

Our group was growing with the progress in neutronography. It was markedly enlarged after I V Kurchatov visited England where he was greatly impressed by the results of neutronographic studies at Harwell. New members of the group included N A Chernoplekov and M G Zemlyanov who had formerly undertaken a study of inelastic neutron scattering on neighboring beams. The phonon spectrum of vanadium; incoherent scattering spectra of protons in lithium hydride; the use of 0-matrices for examining incoherent effects of impurities; and some other findings were their major contributions to the world scientific literature. V A Somenkov and S Sh Shil'shtein who joined the group in 1964 performed illustrious studies on the physical aspects of the interactions between neutrons and crystals, dynamic effects, the structure and dynamics of hydrides, etc. This group, organized in the distant past, continues studies which meet the highest scientific standards.

In 1964, the VVRTs reactor was commissioned at the PCI affiliated center in Obninsk whither we moved all our equipment. In addition, Bacon helped us to purchase a powder neutron diffractometer (from "John Carran" Co) which is still in use. Our old X-ray diffractometer was modified to be used in monocrystal studies which allowed, for the first time in this country, the examination of the structure of molecular crystals with hydrogen bonds. This instrument is also still in good working condition.

At approximately the same time, G M Drabkin and his group initiated neutron scattering studies at the Leningrad Nuclear Physics Institute. They were largely interested in the physical aspects of magnetic neutron scattering. This group is also active today, having on staff S V Maleev, V P Plakhtiĭ, A I Okorokov, V K Trunov, and others.

A major center carrying out neutronographic studies in the Ural region is the Institute of Metal Physics (IMP), Ekaterinburg (former Sverdlovsk). S V Vonsovskiĭ who has been working in this institute for many years, created a school well-known all over the world for the study of magnetism. Naturally, the Laboratory of Neutronography was set up near Sverdlovsk based on the IVV-2M reactor; it was first headed by S K Sidorov and then by B N Goshchinskiĭ (with the participation of A V Doroshenko). The principal task of the laboratory was to study the structure and dynamics of disordered crystals including irradiated ones, disorganized superconductors, magnets, and construction materials.

In the sixties, nuclear reactors were built in all the Republics of the former USSR. Despite an obvious virtue of this ambitious project (a marked increase in the number of high-level specialists), one can not help mentioning its low efficiency coupled to the dissipation of funds assigned for its realization. The work of all the regional neutronographic centers was coordinated at regular meetings of scientists in Moscow, Obninsk, Riga, and other cities, convened on the initiative of IMP.

The construction of the IBR pulse reactor at the Joint Institute for Nuclear Research (JINR), Dubna, was a most valuable contribution to the further development of structural neutronography. In the late fifties, the Soviet government attached great importance to the elaboration of joint research projects with Eastern Europe. JINR and its reactor were created in the framework of this strategy. This pulse source of neutrons turned out to be especially useful in the development of a new technique for neutron structural analysis based on angular (θ), rather than wavelength (λ), unfolding of the spectrum of neutrons scattered in accordance with the Bragg–Wolf law ($n\lambda = 2d \sin\theta$). The wavelength was found from the time over which a neutron traversed a path of a certain length; hence the name 'time-of-flight' (TOF) technique. At that time, the idea of this method was in the air (for example, it was suggested by V Safronov, my fellow-student). It was realized by B Buras first using a 'chopped' neutron beam of constant intensity and then on the IBR reactor, more suitable for the purpose. In JINR, these experiments were conducted by a group consisting of by V V Nits, I Sosnovskiĭ, E Sosnovskiĭ, and R P Ozerov under the guidance of F M Shapiro.

The TOF technique has recently become very popular because pulse neutron sources on atomic accelerators proved to be very helpful for structural analysis in terms of radiation intensity. Such accelerators generate ultra-short neutron pulses which allows the TOF method to be realized at a very small scale with high resolution. At the same time, the relatively broad but rare pulses produced by the IBR-2 reactor require the large size of the devices but allow measurements to be made using quasi-stationary (i.e. relatively long) strong magnetic, electric, and other fields synchronized with the neutron bursts; their realization in the steady state regime appears infeasible. Also, it is worth mentioning the use of IBR-30 in a study of magnetic field effects on hematite monocrystals; to my knowledge, the magnetic-field tension achieved in this study has never been exceeded.

Russian physicists made an important contribution to the theory of interactions between neutrons and solids. Very long ago (in 1950), A I Akhiezer and I Ya Pomeranchuk published a book which helped me to better understand the then new theory of neutron scattering by nuclei. The scientific school founded by Yu M Kagan gave priority to the physics of solids in the context of their neutron scattering capacity. The predicted effects were later confirmed by experiments of the aforementioned group at KI. Specifically, the behavior of heavy elements added to a light matrix, and characteristic features of dispersion curves due to three-particle interactions received a theoretical explanation, a detailed study of neutron propagation in the presence of contaminating atoms at certain points of the crystal lattice was made. In Sverdlovsk, Yu A Izyumov did much work on the theory of magnetism and neutron scattering by solids. In 1961, I was lucky to meet Izyumov on board a ship which hosted a conference on magnetism. We became and remain friends. During our first meeting, we agreed to write a book on the theoretical and practical aspects of neutron scattering on crystals. This work took us several years and ended in the publication of the book which was soon translated into English. It was followed by a series of new books, both in Russian and English, within the next few years. It seems safe to state that so many monographs on neutron scattering have been published in no other country [14].

Izyumov and his disciples related the results of experiments on the structure of magnets to the theory of magnetic ordering and thus provided the basis for neutronographic examination of the magnetic structure in crystals. It is important that this approach can be applied not only to co-linear structures but also to many-axial and incommensurable ones.

To make the picture complete, it is worthwhile to note that the group of scientists (G M Drabkin, S V Maleev, A I Okorokov, I V Naumov, N A Chernoplekov, V A Semenkov, S Sh Shil'shtein, M G Zemlyanov, A Yu Rumyantsev, Yu A Izyumov, and R P Ozerov) won the 1986 State Prize for new methods of solid state studies based on neutron scattering using steady state nuclear reactors as neutron sources.

During the last decade, neutronography has been greatly influenced by two major events. One is the dramatic changes in this country and the well-known concomitant problems. Many research groups have become virtually extinct as a result of 'natural selection' while others reached a higher level of cooperation with foreign laboratories and enjoy access to formerly unavailable means for experimentation. The other factor is competition inside neutronography as a method of structural analysis (e.g. the use of pulse vs. steady state neutron sources) and with other equally advanced techniques such as synchrotron radiation.

The former factor is reality. In the analysis of the latter, I would like to forbear discussing the potential of IBR-2 for the reasons cited above. This reactor must be used to solve specific problems, and its effective exploitation is an important task to be fulfilled in any reasonable way. The merits and demerits of steady state reactors and pulse neutron sources based on particle accelerators are better to compare in the historical view, following the train of thought of physicists and engineers. Analysis of the cumulative intensity of neutron sources, from the earliest Ra – Be source to modern steady state and pulse reactors, indicates that a further increase in the power of steady state reactors is restricted by the impossibility of more efficiently withdrawing heat from the active zone. This limitation does not apply to pulse sources. Therefore, if the intensity of neutron sources needs to be enhanced for the solution of certain scientific problems, the modification of pulse sources is the most promising way to attain the goal.

It is worth mentioning how the achievements in neutronography have recently been acknowledged by the world scientific community. A few years ago, Professor Clifford Shull was awarded the I M Frank prize by a special JINR-based Council. It was clear at the announcement of this decision that this was not the end of the story. Indeed, a year later (1995) Shull and Brockhouse shared the Nobel Prize in physics. We all have reasons to be satisfied with this decision of the Nobel Prize Committee because it means that the science to which we devoted our lives is recognized by mankind. In justice, the contribution of another physicist, Professor G E Bacon, deserves an equally high appraisal.

To conclude, I would like to emphasize the value of this jubilee session which gives an opportunity, on the one hand, to glance back to better understand the laws governing the development of science and technology, and on the other hand, to see future prospects for these forms of human activity.

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Current methods of structural neutronography

Aksenov V L

1. Introduction

The Bragg – Wolf equation suggests two options for obtaining reflexes from a separate atomic plane, at a constant wavelength $\lambda = \lambda_0$ and variable angle of reflection Θ or at a constant $\Theta = \Theta_0$ and variable wavelength. In the former case (*the constant wavelength method*) which is most often realized with continuous flux sources, the experiment is organized in the same manner as in the case of X-ray diffractometry. In the latter case, the relatively low velocity of thermal neutrons allows for the wavelength to be deduced from the time of neutron flight between the source and the detector using the de Broglie relation. The analog of this method [*the time-of-flight* (TOF) *technique*] is γ-quantum spectroscopy in diffraction experiments with X-rays or synchrotron radiation. In neutron diffractometry, the TOF technique is especially effective when pulse neutron sources are used. Its recent modification is the reverse TOF technique. These two methods, used in combination with up-to-date high-flux neutron sources, appear to be most promising for structural neutronography.

2. Time-of-flight method

The first attempt to realize the TOF technique at the reactor at Swierk, Poland, dates back to 1963 even though it was clear even at that time that pulse neutron sources are more adequate for the purpose of TOF diffractometry. Therefore, in the same year, Polish and Russian physicists set off experiments on the first IBR pulse reactor at the Joint Institute of Nuclear Research (JINR), Dubna [1] which was used from the very beginning (since 1960) in studies employing the TOF technique. These were actually the first real experiments in TOF neutron diffractometry. The pioneering experiments at Swierk and Dubna were soon followed by a wide spread of TOF diffractometry to other laboratories in different countries. By the late sixties, TOF diffractometers were already available in the leading research centers of Denmark, USA, Japan, and Great Britain.

The TOF technique was shown to have obvious advantages over the constant wave method [2] which included fixed scattering geometry, the simultaneous measurement of a large number of reflexes, a wide range of neutron wavelengths, the pulsed character of radiation, and high neutron fluxes. This allowed for structural studies to be conducted using additional facilities to induce external impacts such as heating and cooling in a broad temperature range (from ultra-low to ultra-high values), electric and magnetic fields, etc. High-pressure chambers proved very efficient for the analysis of microsamples [3].

However, the potential of TOF diffractometry could not be fully realized until a new generation of high-flux pulse neutron sources came into being. The construction of highly intensive neutron sources based on proton accelerators in Japan, USA (Argonne, 1981; Los Alamos, 1985), Great Britain (1985), and the IBR-2 pulse reactor at Dubna (1984) gave second birth to TOF diffractometry. During the next decade, each new neutron source was equipped with a few TOF diffractometers which were superior to their analogs on steady state reactors in terms of selected parameters.

3. Reverse time-of-flight method

Another breakthrough in TOF diffractometry was the development of a new methodology which coupled the reverse TOF technique with the use of Fourier choppers (neutron Fourier diffractometry).

The idea of applying Fourier transformations to neutron diffractometry first arose at the Brookhaven National Laboratory, USA, in the late sixties, in searching for a method to improve the performance of a TOF diffractometer based on the steady state reactor. It was suggested that the conventional one-slit Fermi chopper be replaced by a chopper having several neutron-transparent slits which modulated the neutron beam so that at an angular frequency corresponding to a certain constant rotation speed of the chopper, the incoming and outcoming signals were periodic functions of the angular velocity (Fourier chopper). Such a modulation prevented the loss of neutron-flux intensity but gave rise to the recycling effect, accounting for the almost complete overlap of the recorded spectra.

The problem of restoration of the diffraction spectra was basically resolved by Finnish physicists at the Center of Technological Research, Helsinki, in the mid-seventies [4]. The solution looked very unusual because the authors disregarded the exact transit-time of each recorded neutron and proposed to estimate the distribution of probabilities to record individual neutrons. Technically, the problem was reduced to estimating the probability of a neutron's having left the source some time ago, passed the chopper, and reached the detector instead of recording the time of its arrival at the detector. This approach is currently referred to as the reverse TOF technique.

The first Fourier diffractometer on a steady state reactor was constructed at the St. Petersburg Nuclear Physics Institute (NPI), Russian Academy of Sciences, Gatchina (near St. Petersburg); the instrument allowed the demonstration of the high performance of neutron Fourier diffractometry [5]. It soon became clear that neutron sources like IBR-2 were most suitable for practical realization of the new technique. History repeated itself. The new method had few advocates — the memory of lame attempts in the late sixties seemed to place a psychological barrier in the way of this mathematically complicated but potentially very effective method.

In 1989, the I M Frank Laboratory of Neutron Physics (JINR), NPI, and the Center of Technological Research, Helsinki, initiated a joint project with the aim of installing a high-resolution Fourier diffractometer (HRFD) on the IBR-2 reactor. Taking advantage of the previous experience of the Helsinki and Gatchina groups, the project was successfully completed in the middle of 1992, and the first high-resolution measurements of diffraction spectra were made on June 11. An international workshop on structural analysis celebrating this event was held at Dubna in September 1992.

Today, this HRFD is one of the four best neutron diffractometers in the world distinguished for the highest resolving power and neutron flux intensity at the sample. It provides a valuable tool for structural studies in physics, biology, chemistry, and the science of materials. The potential of the HRFD is especially demonstrable if the instrument is used to investigate specific structural features of composite substances [6, 7].

4. Conclusions

To summarize, structural neutronography currently uses three essentially different methods. Two of them were first realized in Russia.

The development of Fourier diffractometry and the construction of the HRFD should be considered major achievements in this field. The HRFD is a novel instrument for pulse neutron sources. It opens new prospects for the more efficacious use of the IBR-2 reactor and actually makes it one of the best sources of neutrons in the world. Certain neutronographic centers have initiated projects for the construction of similar diffractometers. There is a serious argument in favor of the priority development of long-pulse neutron sources (of the IBR-2 type). Studies along this line are currently underway.

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Physical basis of magnetic neutronography

Izyumov Yu A

1. Introduction

The corner-stone of magnetic neutronography is the formula for the matrix element $V_{\mathbf{pp}_0}$ of neutron scattering by an atom, with a change in its wave vector $\mathbf{p}_0 \to \mathbf{p}$ [1]:

$$V_{\mathbf{pp}_0} = r_0\gamma F(\vec{\varkappa})\big(\mathbf{s}_\mathrm{n} - (\mathbf{e}\,\mathbf{s}_\mathrm{n})\mathbf{e}, \mathbf{S}\big)\,. \tag{1}$$

Here, $\mathbf{s}_\mathrm{n}$ is the neutron spin, $\mathbf{e}$ is the unit scattering vector, $\vec{\varkappa} = \mathbf{p} - \mathbf{p}_0$, $\mathbf{S}$ is the atomic spin, $F(\vec{\varkappa})$ is its magnetic form-factor, γ is the neutron magnetic moment in nuclear magnetons, and r_0 is the electron electromagnetic radius. The matrix element of scattering from a crystal is obtained by summation of expression (1) over all magnetic atoms at lattice points and the corresponding phase factor $\exp(\mathrm{i}\vec{\varkappa}\mathbf{R}_l)$. The cross-section of elastic magnetic scattering of non-polarized neutrons is found by averaging the squared matrix element $V_{\mathbf{pp}_0}$ over neutron spin orientations in the beam. For a magnetic structure (MS) with the wave vector $\mathbf{k}$, it has the form [2, 3]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = (r_0\gamma)^2(\mathbf{M}^*_{\vec{\varkappa}}\mathbf{M}_{\vec{\varkappa}})\sum_{\mathbf{b}}\delta_{\vec{\varkappa},\mathbf{b}+\mathbf{k}}\,. \tag{2}$$

Here, $\mathbf{b}$ is the arbitrary vector of the reciprocal crystal lattice and $\mathbf{M}_{\vec{\varkappa}}$ is the fundamental vector of magnetic scattering defined by the relations

$$\mathbf{M}_{\vec{\varkappa}} = \mathbf{f}_{\vec{\varkappa}} - (\mathbf{f}_{\vec{\varkappa}}\mathbf{e})\,\mathbf{e}\,, \tag{3}$$

$$\mathbf{f}_{\vec{\varkappa}} = \sum_i \exp(-\mathrm{i}\vec{\varkappa}\,\mathbf{R}_i)F_i(\vec{\varkappa})\,\mathbf{S}_{0i}\,. \tag{4}$$

The vector $\mathbf{f}_{\vec{\varkappa}}$ represents a structural magnetic factor because it is made up of the magnetic moments $\mathbf{S}_{0i}$ of the atoms occupying a unit cell of the crystal.

Expression (2) is the basic formula of magnetic neutronography as a tool for experimental evaluation of MS. The cross-section is defined by the factor $(r_0\gamma)^2 \times 10^{-24}\,\mathrm{cm}^2$; hence, the cross-section of magnetic scattering is of the same order of magnitude as that of nuclear scattering even though its absolute numerical value is normally smaller.

It follows from Eqn (2) that MS is determined by a two-stage procedure. First, the wave vector $\mathbf{k}$ is deduced from the system of Bragg magnetic peaks

$$\vec{\varkappa} = \mathbf{b} + \mathbf{k}\,, \tag{5}$$

then the orientation of magnetic atomic moments in the crystal is found from the intensity of magnetic reflexes. At this stage, $3s$ variables are subject to variation in the adjusting procedure for measured and calculated intensities (s is the number of magnetic atoms in the crystal lattice); the higher s the more complicated the procedure.

The reliability of both stages of magnetic neutronography can be enhanced by applying the crystal symmetry theory in the form of irreducible representations (IR) of spatial groups. The advantage of such an approach is in the possibility of using no magnetic symmetry groups such as the Shubnikov black-and-white symmetry groups or their generalizations (color groups). Instead, the IR apparatus of a spatial crystal group G may be used, which applies to any wave vector, both at and outside the symmetric points of the Brillouin zone. This allows commensurable and incommensurable MS to be described following the common scheme.

Let us first consider the MS wave vector problem. Formula (2) was derived using the following expression relating the atomic spin in the n-th unit cell of the crystal to the spin in the zero cell:

$$\mathbf{S}_{ni} = \exp(\mathrm{i}\mathbf{k}\mathbf{t}_n)\mathbf{S}_{0i}\,, \tag{6}$$

where $\mathbf{t}_n$ is the corresponding translation vector. It should be noted that this relation (which actually defines the MS wave vector) holds true in the strict sense only for the one-ray star of the wave vector $\mathbf{k}$. In the general case, the star $\{\mathbf{k}\}$ has many rays, that is, it contains a set of rays $\mathbf{k}_L$ derived from a given ray by operations from group G. These rays being physically equivalent, expression (6) must be substituted in the general case by a superposition of the ray contributions [2]:

$$\mathbf{S}_{ni} = \sum_L C_L \exp(\mathrm{i}\mathbf{k}\mathbf{t}_n)\mathbf{S}^L_{0i}\,. \tag{7}$$

The translational properties of MS are wholly determined by a set of non-zero mixing coefficients C_L (we call this set the transition channel [2]). It turned out that relation (7) defines one of the 36 lattices with Shubnikov symmetry for all Lifshits stars (i.e. for wave vectors ending at the symmetric points of the Brillouin zone) of fourteen Bravais lattices and for all possible transition channels. Therefore, for commensurable MS to be described there is no need of magnetic symmetry; suffice it to use the spatial group of the crystal and relation (7). Reference [2] presents tables of magnetic reflexes which can be employed to directly determine the transition channel. Normally, experimenters make use of the partial (one-ray) relation (6) to identify the magnetic lattice even in the case of a star $\{\mathbf{k}\}$ having many rays and disregard the general case (7) corresponding to the multi-$\mathbf{k}$-structure. However, it should be borne in mind that it is rather difficult to distinguish between multi-$\mathbf{k}$ and 1$\mathbf{k}$-structures because the set of domains in a 1$\mathbf{k}$-structure produces the same magnetic reflex pattern as in a multi-$\mathbf{k}$-structure. The latter can be identified by examining the very subtle concomitant phenomena responsible for the difference between multi-$\mathbf{k}$ and 1$\mathbf{k}$-structures. The MS of $\mathrm{CeAl_2}$ may serve as an example [2].

Let us consider the symmetric aspects of the second stage of magnetic neutronography at which the orientation of atomic magnetic moments $\mathbf{S}_{0i}$ is determined. $\mathbf{S}_{0i}$ values should be expanded in basic functions of IR of the wave vector group $G_\mathbf{k}$:

$$\mathbf{S}_{0i} = \sum_\nu\sum_\lambda C^\nu_\lambda \mathbf{S}\begin{pmatrix}\mathbf{k}\nu\\ \lambda\end{pmatrix}\Big|\,i\Big)\,. \tag{8}$$

Summation over ν is performed over all IR of the $G_\mathbf{k}$-group and over numbers λ of the basic functions of its multi-dimensional IR. $\mathbf{S}(^{\mathbf{k}\nu}_{\lambda}|i)$ values are given in the basis of axial vectors, in the same manner as atomic displacements are expanded in a crystal in the polar vector basis. The atomic components of the basic functions $\mathbf{S}(^{\mathbf{k}\nu}_{\lambda}|i)$ can be calculated for any crystal provided the magnetic atom coordinates in the cell and the MS wave vector are given. We have developed effective methods for calculating these values (magnetic modes) which are described in Ref. [2].

It follows from the Landau theory for second order phase transitions that MS may be described by a single IR of the $G_\mathbf{k}$-group; in other words, the partial relation

$$\mathbf{S}_{0i} = \sum_\lambda C^\nu_\lambda \mathbf{S}\begin{pmatrix}\mathbf{k}\nu\\ \lambda\end{pmatrix}\Big|\,i\Big) \tag{9}$$

holds. Therefore, MS may be given by a set of mixing coefficients C^ν_λ (at fixed ν). Since the IR of spatial groups most often have the dimension $l = 1$, 2, 3 (sometimes 6), hypothesis (9) suggests that MS is given by a small number of C^λ_λ values subject to variation in the procedure of adjusting observed and theoretical intensities. Since the IR responsible for MS is initially unknown, it is necessary to test all possible

IRs of the $G_{\mathbf{k}}$-group in succession; each time, only a small number of parameters will undergo variation. In the end, the smallest resulting R-factor should be chosen. The reduction in the number of parameters subject to variation, from 3σ to l, is the purpose of the described symmetry analysis in magnetic neutronography.

How does the hypothesis of one IR for MS work? The symmetry analysis of a large number of MS reported in the Ref. book [4], the supplement [5], and also in Ref. [2] has shown that in the majority of cases MS corresponds to a single $G_{\mathbf{k}}$-group IR. Exceptions to this rule are usually of symmetric nature due to three main reasons: high symmetry of the exchange Hamiltonian, the praphase effect, and the so-called concomitant IR (see [2] for details and examples). If the MS being examined corresponds to several IR, and this fact can not be accounted for by the above reasons, there is a high probability of experimental error.

Relations (8) and (9) accentuate the importance of calculating the basic functions $\mathbf{S}\binom{\mathbf{k}\nu}{\lambda}|i)$ for the evaluation of MS. Based on the methods reported in Ref. [2], the Cracow group has developed a software system (450 kilobytes) for the calculation of these functions for a given crystal and wave vector which allows them to be obtained without knowing the apparatus of the IR theory for spatial groups. The same group currently creates a computerized database of all MS with the results of symmetry analysis by our method [2] and a software package for the retrieval of information about MS using different parameters.

This database is expected to allow the derivation not only of a map showing the orientation of magnetic moments but also data on its transformation under the effect of crystal symmetry operations, i.e. to identify the IR group of the wave vector and transition channel. This group theory information constitutes the true MS passport which provides the starting point for in-depth MS investigations, e.g. elucidation of specific features of MS magnetic phase transitions and behavior in external fields.

This approach is equally applicable to commensurable and incommensurable (modulated) MS [8, 9], i.e it is a universal approach. Hence, the description of MS in terms of magnetic symmetry groups is unnecessary, the apparatus of the theory of spatial group representations being more convenient, simple, and universal. However, it should be noted that Shubnikov groups are useful for the examination of elementary excitation (spin wave) spectra because spin waves are classified based on irreducible co-representations of these groups, similar to the way ordinary phonons in a crystal are classified by the IR of spatial groups [9].

Now, let us consider the effects of polarized neutron scattering from MS. The main aspects of elastic and inelastic scattering were explored in Refs [10, 11], and the results were used to develop a polarization analysis for magnetic neutronography. There are two principal effects: the dependence of the scattering cross-section on the orientation of the polarization vector of an incident beam and a change in the beam polarization as a result of scattering. The two effects are fully characterized by the same magnetic vector $\mathbf{M}_{\vec{\varkappa}}$ (3) which defines the cross-section of non-polarized neutron scattering. Indeed, an initially non-polarized beam scattered from an MS into a Bragg magnetic peak with $\mathbf{k} \neq 0$ undergoes spontaneous polarization with the polarization vector [2, 3]

$$\mathbf{p} = -\frac{-\mathrm{i}[\mathbf{M}^*_{\vec{\varkappa}} \times \mathbf{M}_{\vec{\varkappa}}]}{(\mathbf{M}^*_{\vec{\varkappa}}\mathbf{M}_{\vec{\varkappa}})} . \qquad (10)$$

In principle, the use of the one IR hypothesis (9) allows MS to be identified from a single reflex provided it is measured at three mutually perpendicular orientations of the polarization vector. Relation (10) also shows that purely magnetic scattering from an antiferromagnetic structure can serve as a source of polarized neutrons. This approach differs from the traditional method of generating a polarized neutron beam using the superposition of nuclear and magnetic scattering at a ferromagnet crystal. To conclude, it should be pointed out that the effects of inelastic neutron scattering at spin waves and non-linear excitations (solitons) are discussed at greater length in Refs [11] and [12] respectively.

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Neutron scattering and investigations in solid state physics in the St. Petersburg Nuclear Physics Institute

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1. Introduction

The decision to build a reactor at the A F Ioffe Physico-Technical Institute (PTI), Gatchina, required the choice of a research area in which neutron scattering could be most efficiently employed. At that time (the late fifties), the country had no practical experience in this field even though the theoretical aspects of the problem were elaborated fairly well, e.g. in the works of A I Akhiezer and I Ya Pomeranchuk [1]. Moreover, PTI had an established scientific school well-known for research on the scattering of polarized particles and related processes. I M Shmushkevich suggested that I investigated polarized neutron scattering in magnets. G M Drabkin joined PTI at approximately the same time and chose polarized neutrons as a principal tool for his studies. This proved to be a happy choice.

Since then, polarized neutron scattering remains a priority problem in PTI. Certainly, other lines of research have been developed in parallel including high-resolution powder diffractometry and magnetic neutronography. Studies using neutron refractometry are currently underway. The high level of neutron research at PTI allowed 17 scientists to participate in the European conference on neutron scattering in October 1996; twelve grants were awarded to them by foreign agencies and institutions. It is most gratifying that eight of the participants were young people. Various instruments for neutron studies designed and manufactured in PTI (polarizers, neutron-guides, flippers, etc.) are widely used in many foreign laboratories. The following examples illustrate the different ways in which neutrons are used in PTI to study solids. The examples are somewhat arbitrary and far from being exhaustive because of the limited size of this communication.

2. Structural neutronography

A high-resolution Fourier diffractometer was designed and created in the laboratory headed by V A Trunov; it is comparable with similar instruments on high-flux reactors and pulse neutron sources (ILL, Aragon, RAL) in terms of basic parameters [2]. The diffractometer was employed in many structural studies of different classes of chemical substances such as formiates [Re(DCOO)$_3$, where Re = Y, Ce, Sm, La, Tb, Tm] [3], hexaborides Re^{11}B$_6$ (Re = Y, Ce, Sm, La, Nd) [4, 6], and high-temperature superconductors [7, 8]; it was also used to evaluate the effects of thermal treatment of tool steel. By way of an illustration, a study of SmB$_6$ using a mixture of ^{152}Sm and ^{154}Sm isotopes demonstrated the possibility of completely suppressing coherent scattering of samarium and examining the boron subsystem in the pure form [4]. As a result, the study revealed a large concentration of boron vacancies ($\sim 4\%$) and made it possible to measure boron thermal factors. This experience provided the basis for the examination of the entire ReB$_6$ series and the identification of thermal factors of both boron and metals [5] which turned out to be well-described by the Einstein model.

Magnetic structures are investigated in the laboratory headed by V P Plakhtiĭ. One of the most interesting results of these studies is the discovery of weak antiferromagnetism in yttrium orthoferrites [9]. The authors took advantage of the spin-flip that occurs when neutrons undergo magnetic scattering and distinguished a Bragg scattering component associated with weak antiferromagnetism. The weak to main component ratio in the spin was found to be $1.93(18)\times10^{-2}$.

Recently, there has been increasing interest in the properties of thin layers and multilayer structures with reference to the problem of gigantic magnetoresistivity and the prospect of using such systems in memory units. This dictates the necessity of studying the real structure of multilayer systems. Their manufacture by vacuum deposition is known to be complicated by fluctuations of the interface relief which are best characterized based on reflection and scattering patterns of neutrons and X-rays. Polarized neutrons are used to evaluate the magnetic properties of multilayer structures. Such studies have recently been initiated in PTI [10]. The analysis of the irregular reflection of neutrons from a system composed of alternating cobalt and titanium layers yielded a map of intensity distribution (Fig. 1). It shows the mirror reflection line ($\alpha' = \alpha$) with the quasi-Bragg peak at $\alpha = (\lambda/2d) = \alpha_B/2$, where $d = 75$ A is the structure period, as well as Bragg scattering along the line $\alpha + \alpha' = \alpha_B$ which suggests a correlation between roughnesses in the direction perpendicular to the layers (conformal roughness).

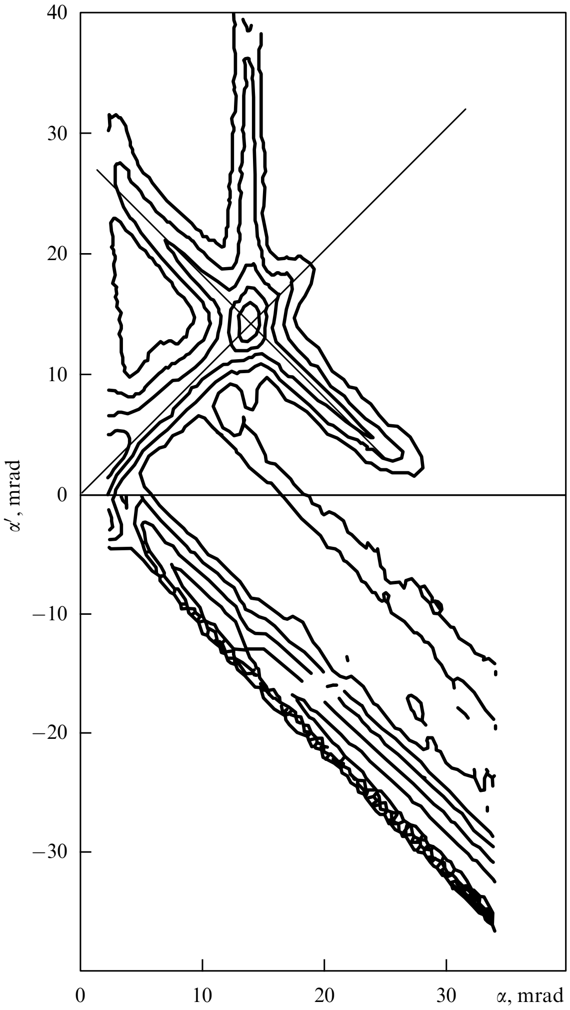

Figure 1. A map showing the intensity of reflexes from a system consisting of 20 pairs of Ti and Co layers (the thickness of each layer is 37 A).

3. Inelastic scattering

Today, there is only one PTI-owned three-axis spectrometer (Neutron II) on the BBP-M reactor. To illustrate the results obtained with this instrument, it is worth mentioning a study on the lattice dynamics in a segnetoelectric relaxor PbMg$_{1/3}$Nb$_{1/3}$O$_3$ [11]. The examination of low-lying acoustic modes revealed their strange dependence on the reciprocal lattice point suggesting strong non-linearity of the lattice in the longwave limit. Analysis of these data was used to predict an additional soft mode in the narrow vicinity of the center of the Brillouin zone. The existence of such a mode was later confirmed by experiment. A drop in temperature was shown to turn it into the central peak related to local segnetoactive lattice distortions.

The group headed by V P Plakhtiĭ obtained very interesting data on antiferromagnetic garnets having magnetic sublattice systems which do not interact in the molecular field approximation. For example, $Mn_3Cr_2Ce_3O_{12}$ was found to have two Néel points $T_N = 5.1$ K and 3.9 K in the chromium and manganese sublattices respectively [12]. E F Shender demonstrated that spin waves, e.g. zero oscillations, must lead to fluctuation interactions between sublattices [13] which align them relative to one another (i.e. create order from disorder) [14–17] and eliminate the degeneration of spin wave acoustic branches at $\mathbf{k} = 2$. This accounts for the appearance of the quantum gap found in Ref. [14].

4. Polarized neutrons. General remarks

Neutron polarization $\mathbf{P} = \langle \boldsymbol{\sigma} \rangle$ is a three-dimensional t-odd axial vector. The variables to be measured are the cross-section dependence on the initial polarization $\mathbf{P}_0$ and the post-scattering polarization. In a full-scale experiment, the initial polarization $\mathbf{P}_0$ is given in three mutually perpendicular directions and three polarization components are measured after scattering. This is the so-called three-dimensional analysis which was first performed by A I Okorokov and co-workers [15]. However, it requires a high-flux neutron beam. Therefore, scattering cross-sections both with spin-flip and without are usually measured [16]. The theoretical basis of this method was developed in Ref. [17].

5. Interaction between neutrons and large-scale magnetic inhomogeneities

Scattering experiments are usually concerned with magnetic inhomogeneities $\delta \lesssim 10^{-5} - 10^{-6}$ cm in size. Sometimes, however, bigger inhomogeneities have to be examined. This is achieved by measuring the polarization of a neutron beam which passes through the sample without a marked change in traveling direction. In the case of large inhomogeneities ($\delta \gtrsim 1$ mm), the polarization vector of the neutron beam swings due to precession in the inhomogeneity field. It is sometimes possible to restore the distribution of magnetization inside the sample by scanning it with a thin beam and measuring a change in the direction of polarization with the aid of three-dimensional analysis. This method is inapplicable in the case of smaller inhomogeneities (10^{-1} cm $> \delta > 10^{-5}$ cm) although the emerging neutron depolarization may also be used as a source of detailed information about magnetic inhomogeneities.

6. Visualization of the trapped field in superconducting ceramics [18]

A superconducting ceramic is a Josephson medium which simulates a hard superconductor of the second type with $H_{c1} \sim 10^{-3} - 10^{-1}$ Oe. The scanning of a polarized neutron beam along the x axis was used to examine the distribution of the field trapped in $YBa_2Cu_3O_{7-\delta}$. The sample was cooled to below T_c in the zero-field which was then aligned along axis z, turned at an angle Φ to the plane (zy), and shut down. The x-dependence of the average trapped field distribution shown in Fig. 2 is in good qualitative agreement with the Bean theory [19]. The field direction also shows x-dependence. It is inferred that macroscopic superconducting currents have components perpendicular and parallel to the induction vector.

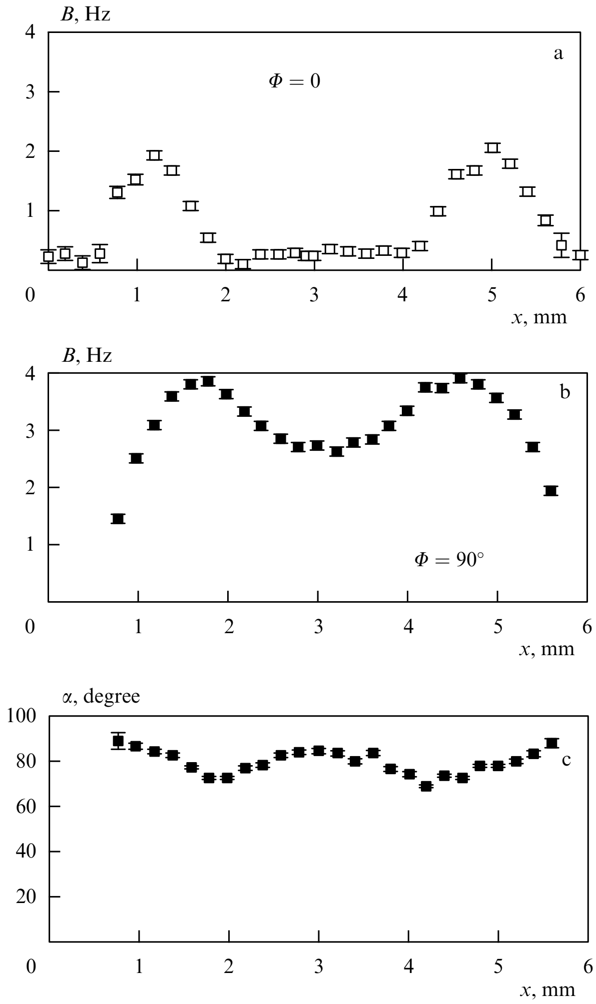

Figure 2. Dependence in a sample of average field distribution (a, b) and direction (c) on the depth x at $T = 60$ K, $H = 7.5$ Oe.

7. Neutron depolarization

In the case of small magnetic inhomogeneities, the polarization of the beam that passes through a sample changes due to random spin turns, and the beam undergoes depolarization [20]. However, interaction of the neutron with a homogeneity of size δ leads to a change of the order of $\hbar/\delta$ in its momentum, that is, it undergoes scattering. As a result, the beam contains neutrons which experience small-angular magnetic scattering unresolvable by the device [21]. In the case of magnetic scattering from inhomogeneities, the polarization has the form [21]

$$\mathbf{P} \propto \langle \mathbf{M_q}(\mathbf{M_q}, \mathbf{P}_0) \rangle - \langle \mathbf{M_q}, \mathbf{M_{-q}} \rangle \mathbf{P}_0 \,,$$

where $\mathbf{M_q} = \mathbf{m_q} - (\mathbf{m_q}, \mathbf{q})\mathbf{q}/q^2$ is the Fourier component of magnetization $\mathbf{m}(\mathbf{r})$ perpendicular to the transferred momentum $\mathbf{q}$. In the end, the depolarization turns out to be dependent on the reciprocal orientation of the neutron velocity vectors $\mathbf{P}_0$ and the magnetic anisotropy of the sample. For a magnetically isotropic sample, the neutrons polarized parallel and perpendicular to their velocities are depolarized in a different manner, with $\ln \Gamma_\perp / \ln \Gamma_\| = 3/2$, where $\Gamma_{\perp,\|} = P_{\perp,\|}/P_{0,\perp,\|}$. There is no such relationship in the case of anisotropic samples, and the depolarization shows a strong dependence on the reciprocated orientation of the velocity $\mathbf{P}_0$ and the anisotropy. This phenomenon was investigated for a $Pd_{0.96}Fe_{0.04}$ alloy near $T_c = 120$ K; the anisotropy was created by external pressure.

The depolarization of a beam passing through a sample is described by the expression

$$\mathbf{P} = \mathbf{P}_0 \exp\left(-\frac{L}{l_\psi}\right),$$

where L is the sample thickness and l_ψ is the free path for scattering inside a straight beam. At the same time, the neutron beam attenuation due to outside scattering has the form

$$I = I_0 \exp\left(-\frac{L}{l}\right),$$

where l is the corresponding free path. If the scattering occurs largely outside the straight beam, $l \ll l_\psi$. This premise was experimentally verified for a ferromagnetic invar $Fe_{75}Ni_{25}$ in the vicinity of the Curie point [23]. It has been shown that l significantly increases with a drop in temperature below $T_c\, l_\psi$. In other words, very strong magnetic scattering occurs at inhomogeneities the size of which is significantly greater than the radius of critical fluctuations. This 'second scale' problem is extensively discussed in the current literature (see, for instance, Ref. [24]).

To sum up, neutron depolarization is a simple method for examining magnetic inhomogeneities which differ in size from those revealed by ordinary scattering.

8. Spin chirality

The concept of spin chirality was called into being by studies of spiral magnetics (Ho, Tb, $CsMnB_3$, etc.) whose structure is described by the expression

$$\mathbf{S}_\mathbf{R} = \mathbf{a}\cos\mathbf{kR} + \mathbf{b}\sin\mathbf{kR}.$$

Chirality may be defined as the product $[\mathbf{a}\times\mathbf{b}]$ or, in the general case, $\mathbf{S}_{\mathbf{R}_1}\times\mathbf{S}_{\mathbf{R}_2}$ [25]. Statistical chirality can be estimated from the $\mathbf{P}_0$-dependence of the elastic scattering cross-section (see below). Fluctuations of chirality are described by a four-spin correlation function, but there is currently no method for their investigation. For a sample placed in a magnetic field, the inelastic scattering cross-section was shown to depend on the neutron polarization [26, 27] expressed through the projection of the chirality operator on a sample magnetization called the dynamic chirality [27]. In weak fields, it is apparent in those regions of space $(\mathbf{q}, \omega)$ and T where the system becomes soft and strongly non-linear.

Dynamic chirality studies have proved very fruitful in cases of small-angular scattering in ferromagnets, by virtue of an integral technique [28] which makes it possible to work with small transferred pulses q and energies ω, in contrast to traditional neutron spectroscopy. Inelastic magnetic scattering is easily differentiated from nuclear scattering due to the $\mathbf{P}_0$-dependence of the chiral part of scattering. Figure 3 illustrates such a differentiation for an amorphous ferromagnet $Fe_{50}Ni_{22}Cr_{10}P_{18}$. This method was also used to derive the spin wave rigidity coefficient near T_c [28]. Further chiral scattering studies in the same material allowed the determination of the spin wave rigidity coefficient and decay rate and the examination dipole interaction at low temperatures [29].

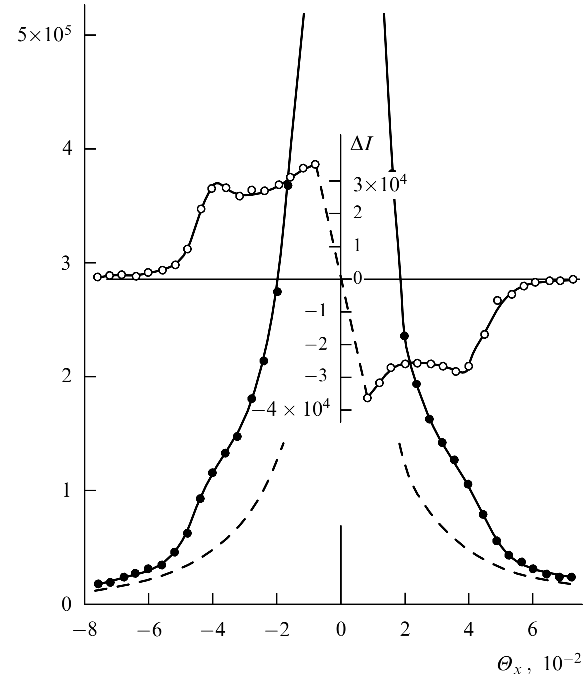

Figure 3. The chiral part of small-angular scattering in $Fe_{50}Ni_{22}Cr_{10}P_{18}$: — — — — straight beam contour, • — total small-angular scattering; ○ — chiral scattering.

Chiral scattering in iron at $T = T_c + 1$ K was used to study the transition from exchangeable critical dynamics to dipole dynamics [30]. This transition failed to be revealed by conventional neutron spectroscopy because of the small values of the corresponding quantities q and ω.

Chirality is not an essential (critical) variable in ferromagnets whereas it is an important one in triangular antiferromagnets ($CsMnBr_3$, etc.) [25]. Therefore, dynamic chirality studies are apt to yield principally new information. Experiments to this effect are planned by V P Plakhtiĭ's group.

9. Steady state chirality

In centrosymmetrical crystals the two directions of the spin-helix screw are energetically equivalent. As a result, the average statistical chirality of the sample $\langle\mathbf{K}\rangle$ is zero and the $\mathbf{P}_0$-dependence of the scattering cross-section disappears. Several methods for preparing samples with $\langle\mathbf{K}\rangle \neq 0$ have been proposed. For example, it was shown [31] that the parity non-conservation of the weak interaction may give rise to helices. This effect failed to be observed in the studies carried out in the laboratory headed by Plakhtiĭ; however, it was demonstrated that the plastic torsion deformation of Ho leads to an uneven population of right and left helices at the level of 2×10^{-2}. This phenomenon can be understood only on the assumption of a new interaction between the torsion strain and the spin chirality which may be phenomenologically presented in the form

$$W = \sum_{\mathbf{R}_1,\mathbf{R}_2} g(\mathbf{R}_{12})[\mathbf{S}_{\mathbf{R}_1}\times\mathbf{S}_{\mathbf{R}_2}]\,\mathrm{rot}(\mathbf{U}_{\mathbf{R}_1}-\mathbf{U}_{\mathbf{R}_2}),$$

where $\mathbf{U}_\mathbf{R}$ is the displacement $\mathbf{R}$ of a lattice point caused by deformation.

To summarize, the St. Petersburg Nuclear Physics Institute has a reputed school of neutron scattering studies which has published many important results. However, further prospects of its work are obscure. The BBP-M reactor has been working since 1959, that is, for about its natural lifetime, and there is only a faint hope that the construction of the new high-flux "PIK" reactor will be completed in the near future.

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